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LeanCost: knowledge-based tool for early product cost estimation

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Abstract

Purpose:
In a scenario characterized by high competitiveness, companies have to apply methods and tools in order to respond to the customer needs while maintaining a constant control on product cost. For this objective, product designer should evaluate different design alternatives by using criteria related not only to function but also to manufacturability and cost. The idea of the present approach is to provide designers with a Knowledge-Based (KB) tool (called LeanCost) that analyzes the product design information by using a manufacturing knowledge base in order to automatically obtain the estimation of manufacturing cost.

Method:
The method proposed in this work originates from the concept that several company departments (product design, process engineering and purchasing) should base their activity on a shared cost model and a related cost estimation tool. The approach is schematised as a single cost estimation software, used in the three main phases of the product development process (design, industrialization and manufacturing). When this kind of software will deployed by a company, each designer will use a Knowledge-Based (KB) tool that analyzes the product design information by using a manufacturing knowledge base in order to automatically obtain the estimation of manufacturing cost.

Result:
In order to evaluate the reliability of this estimation software tool, it is relevant to gather experimental results and evaluate deviation between the standard cost and the estimated one. Standard cost is that one manually calculated by product engineering, while estimated cost is calculated by the designer using the estimation tool. Results analysis will provide useful information to improve the reliability of LeanCost, in terms of parameters and functions.

Discussion & Conclusion:
The LeanCost software tool has been appreciated for its fast and ease of use on almost all the operations required to produce mechanical components, especially for carpentry and sheet metal operations. Improvements are related to the recognition of manufacturing features on 3D CAD models represented by neutral data formats, such as .STEP and . IGS.

1 Introduction

Market globalization drastically increased competitiveness. Customers ever more have the possibility to choose products by evaluating a large number of market proposals. In this context, if a company is able to offer high quality customized products in a reasonable delivery time can gain relevant market shares. Anyway personalised products imply new efficient and agile approaches along the whole product development process, from ideation to manufacturing. In this scenario, companies have to apply methods and tools in order to respond to the customer needs while maintain a constant control on product cost. Manufacturing cost is one of the main important aspects. It should be evaluated in the early design phases in order to rapidly compare different customized technical solutions.

Manufacturing cost estimation is complex due to the huge amount of information that influences the result. In fact, it is necessary to decide which manufacturing process should be adopted, which manufacturing parameters should be chosen, which materials, which equipments have to be realized, the size of production lot, etc. On the other hand, the product designer in the early design phase has at disposal only a preliminary 3D CAD model that has been mainly conceived in order to satisfy the functional requirements. This dichotomy generates errors and numerous iterations between design and manufacturing departments. A consistent improvement can be achieved if product designer can evaluate different design alternatives by using criteria related not only to function but also to manufacturability and cost. In order to overcome this problem, manufacturing knowledge should be shared across the company and used as one of the drivers of product design.

The idea of the present approach is to provide designers with a Knowledge-Based (KB) tool that analyzes the product design information by using a manufacturing knowledge base in order to automatically obtain the estimation of manufacturing cost.

The 3D feature-based CAD model contains the product structure that is concretized through geometrical features, components, assemblies, and not geometrical data (roughness, tolerances, material, etc.). The knowledge-based tool analyzes the CAD data structure and extracts the design information it needs. Manufacturing and process planning rules are collected in the knowledge base. The manufacturing operations are automatically linked to the design features. In order to make this combination in a robust way new clusters of data, called advanced manufacturing features and simple modelling features, are defined. Finally, after design and manufacturing features mapping, the system generates the cost estimation.

Currently, the developed software tool manages the main mechanical manufacturing operations from machining to welding. Starting from the shared knowledge base it has been conceived to be used in different company departments: the design department, the product-engineering department and the purchasing department. The tool is under test in collaboration with a company that realizes woodworking machines.

The paper, after a brief review of the research background (section 2), describes the manufacturing product costing methodology (section 3) and the implemented software tool (section 4). Numerous examples are reported (section 5) in order to evaluate the software system usability and reliability.

2 Research background

The Design for Cost (DfC) methodologies have been studied and formalised since 1985 [1]. The DfC problem can be resumed in the following way: studying and developing methods and tools allowing the designer to calculate costs in the early design phase by managing the knowledge of production processes and, hence, costs incurred therein [2]. Many CAPP (Computer Aided Process Planning) systems have been developed during the last years but they are too complex to be used in the design phase because they require a lot of information beyond the product characteristics and they are, generally, not available during the first stages of design process.

A large number of approaches and methods for cost estimation have been presented in literature [3]. An interesting classification has been reported by Duverlie and Castelain [4]. In Niazi et al. [5] a detailed review of the state of the art in product cost estimation covering qualitative and quantitative techniques and methodologies are described. The qualitative techniques are further subdivided into intuitive and analogical, and the quantitative ones into parametric and analytical. A recent review concerning the cost estimation software systems usable during the product development process is reported in Cheung et al. [6].

According to Weusting et al. [7] cost estimation can be divided into two basic methodologies: generative cost estimation and variant based cost estimation. In the first case, the estimate is based on the decomposition of costs related to the expected production processes. In the second case, the analysis of similar past products allows the evaluation of new ones. It can be stated that a suitable cost estimation tool should include a combination of these two approaches. Feature-based costing [8] can be considered an optimal compromise between them. In fact, features can be used in order to describe the geometric information of product at different levels of detail, and they can be used to collect all functional and technological information (tolerances, surface finishing, manufacturing cycle, etc.). Yet, features defined in a previous product can be reused for the new solutions inheriting all process information.

Parametric feature-based 3D CAD modeling systems can provide the practical support to manage cost information along with functional product definition and its virtual representation. Several feature-based costing technology applications are reported in scientific literature, an overview is provided in Layer et al. [9]. For example, in Ten Brinke [10] an interesting system for estimating costs of sheet metal components is described.

However, there exists no satisfactory computer-aided support for the cost estimation task related to all manufacturing operations domain. Important research works have been carried out in machining operations [11-12], but the developed systems are not well integrated in the design process flow. An improvement has been described in aircraft design field by Watson et al. [13]. An approach where cost estimation has been applied during design phase is reported also in Germani et al. [14]. The work shows how a cost estimation method can be used effectively within a framework in order to manage the configuration of a product variant. Other interesting cost estimation approaches usable in the early design phases are described in Shehab and Abdalla [15] and Mauchand et al., [16]. Both papers propose methodologies and tools in order to support designer choices oriented to optimise manufacturing cost at early design phases, i.e. selection of material, selection of process etc. These rules are important in conceptual design phase. An interesting applicative example representing a step towards the applicability of cost estimation in the early design stage is reported in Castagne et al [17].

From a technological point of view commercial software packages are not still available for cost estimating without excessive effort in manufacturing process modelling, i.e. Delmia by Dassault Systemes.

The proposed system try to overcome the state of art by developing a robust KB system able to support the whole product development process in the most critical phases by providing the right level of detail of product cost information.

3 Design to cost approach

During a generic product development process, mainly three company departments are involved in product costing. Firstly, product design department where product cost is created by adopting specific technical solutions. Secondly, process engineering department where product feasibility is studied, manufacturing operations are defined and, thus, detailed cost is calculated. Finally, the purchasing department that interacts with the supply chain in order to establish prices and choose the best suppliers.

Engineers of these three departments interact with product cost from different viewpoints. Product designers need to understand the incidence of a single cost feature on the total manufacturing cost without a specific skill on manufacturing operations during the design phase. Product engineers (or manufacturing technologists) possess the specific knowledge about the manufacturing activities necessary to determine the detailed cost. Purchasing staff is interested to the cost calculated by the product engineers, in order to select the supplier for every component.

The proposed approach originates from the concept that above departments base their activity on a shared cost model and a related cost estimation tool. In this way are avoided problems due to a scarce awareness of designers to the cost problem, shifting toward the product engineers all cost evaluation activities. Such a situation implies errors and, consequently, numerous and time-consuming iterations. The approach is schematised in figure 1where a single software cost estimation tool is used in the three main phases. This work aims to overcome the problem by developing a software tool dedicated to the design department but also providing a specific view of the product cost model for the other two user typologies (figure 1).

A shared manufacturing knowledge base is used as key element in order to define this multilevel framework.

In order to make usable this framework to all users, it is necessary to develop a detailed estimation method aimed to satisfy the deepest user, who is the product engineer.

Estimation methods can be classified in four typologies: intuitive, analogical, parametric and analytical. Among them, the most coherent with the proposed objective is the analytical method. In fact, it allows evaluating the product cost by the decomposition of work required into elementary activities (an example of an elementary activity is a machine tool operation).

Evaluating production processes for the company's components, this tool gives information also for a processes optimization. Analysing each file generated by LeanCost, it's possible to understand all the operations required for components production, in order to define a set of standard processes which must be used for product machining, with the aim to reduce the overall production costs.

Manufacturing processes have been classified in six groups, called environments: chip forming, carpentry, painting, covering, heat treatments and shaping. Each environment is further composed by several groups of operations, such as milling, turning, grinding, broaching, etc., for chip forming environment. In conclusion, a group contains the operations which are used to define the component working schedule (external cylindrical turning, external cylindrical slot, etc, for the turning group).

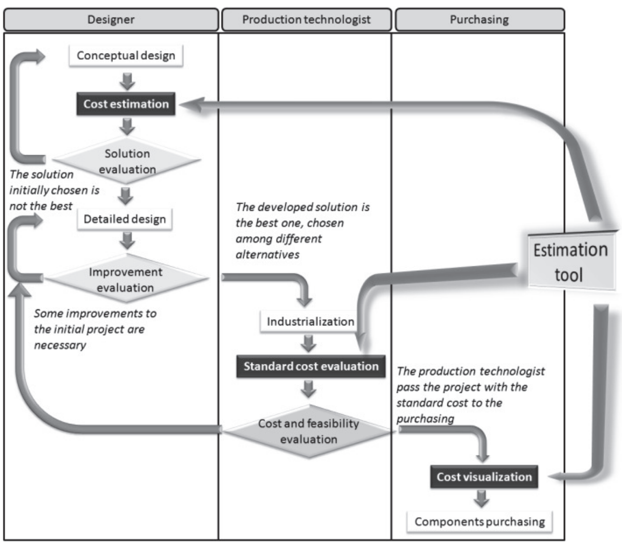

Fig. 1 Cost estimation process related to the three different departments.

At the design stage, by using the analytical approach it is necessary to determine all activities needed for component/assembly manufacturing. While product engineers have experience for cost estimation, the designer rarely has the same kind of knowledge. Hence, it is essential to formalise the manufacturing knowledge in order to apply it during the early cost evaluation.

The product engineer knowledge has been structured in order to support the analysis of product design information and translate it in manufacturing operations and, hence, in manufacturing cost.

Manufacturing technologies have been analyzed and divided into classes as follows: chip-forming machining, mechanical carpentry, painting, thermal treatments, superficial covering, metallic alloy molding and plastic molding. Classes have been further divided into categories, for example the machining class has been subdivided in milling, turning, grinding, gear cutting, broaching and slotting. Within these category have been defined the operations, for example typical operations for milling are face milling, slot execution, etc. Then, the geometrical parameters have been determined in order to univocally characterize the operations. For example the face milling operation is characterized by length, width, depth, geometrical tolerance (planarity) and roughness.

In the proposed knowledge base, the operation is the most important level of data aggregation.

The operations have been univocally mapped with a specific set of geometric and non-geometric elements that have been defined advanced manufacturing features. In this way the product model can be represented as a collection of advanced manufacturing features and simple modelling features. The recognition of these features on the product model allows establishing the operations and their sequence.

In more detail advanced manufacturing features are a set of geometrical elements (faces and axis) conveniently arranged in a recognisable topological shape with specific dimensional constraints and with specific manufacturing information (tolerance and roughness). This information determines a group that can be associated to a specific operation. Feature recognition algorithms deployed in LeanCost, analyze the body of specific CAD model, enriched by user with several Product Manufacturing Information (PMI), such as roughness and dimensional tolerances. During the analysis phase, faces, edges and vertices (topological information) with relative geometrical information, are taken in consideration and compared with the advanced manufacturing features, during iterative processes (FOR cycle), with the aim to establish if a group of faces could be machined with the manufacturing feature of the ith step of FOR cycle.

Advanced Manufacturing Feature	**Definition**
External cylindrical slot	External cylindrical surface enclosed by surfaces with a diameter greater than reference one, and the cylinder length is greater than 6 mm., furthermore it should be guaranteed the radial accessibility of the tool
External cylindrical turning	External cylindrical surface which does not have any faces with a radial range greater than the machining surface diameter, moving from the machining surface to the tailstock, furthermore it should be guaranteed the radial accessibility of the tool.
Frontal slot	Planar surface enclosed by cylindrical surfaces (one external and the other internal) in order to form a solid angle greater than π. It should be guaranteed the axial accessibility of the tool.

Tab. 1 Examples of advanced manufacturing features.

The advanced manufacturing features have been defined because it is not always possible link the CAD modelling feature to a machining operation. In many cases, in fact, in order to manufacture a feature it could be necessary more than one operation, otherwise more features could be machined with a single operation. This problem is typical for the chip forming machining, where different ways could be adopted in order to realize a component. In the following table (table 1) examples of advanced manufacturing features are reported.

In other cases the simple CAD modelling features can be directly linked to the operation; for instance the thread hole definition as represented in the CAD model data structure is sufficient to determine the corresponding operation.

The second knowledge level is oriented to the determination of manufacturing cost, starting from the operations list with their geometrical parameters. This level is based on the definition of algorithms that the product engineer uses in order to determine all technological parameters necessary for cost estimation process. These algorithms need a lot of data (raw material cost, standard equipment time, etc...) and relations (material-cutting speed, material,-machine-tool-feeding rate, welding speed-bead dimension-material, etc...) that can be stored within a technological database. The values extracted from the database are elaborated by specific formulas used to calculate the estimation parameters and the final component cost. Typical formulas, within the metal working machines field, are those used for the calculation of tool paths length, working time, cost, etc.

In order to understand how the proposed approach is able to estimate the manufacturing cost a simple example is reported. It interests the external cylindrical slot advanced manufacturing feature (figure 2). The taxonomic definition of this feature is reported in table 1.

The data structure of the 3D CAD model is analyzed and proper algorithms compare the definition of external cylindrical slot feature with the geometric model in order to recognize it with its geometrical parameters (on the basis of classification as in table 1): initial diameter (Di), final diameter (Df), radial allowance (P), slot length (L) and roughness (R).

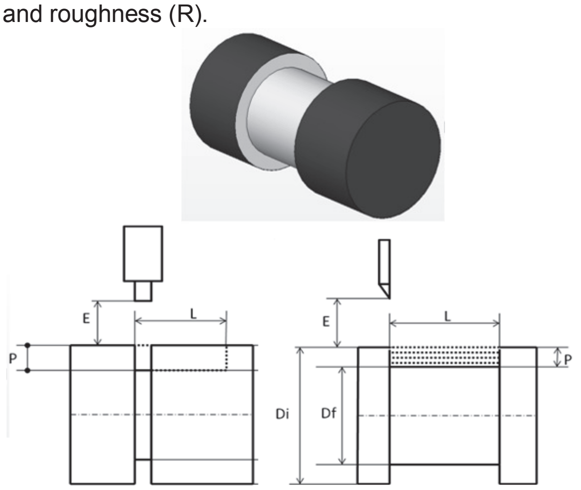

Fig. 2 Grey faces represent the external cylindrical slot. In the centre and below the first and second phases of the turning operation are respectively shown.

Once the geometry has been identified it is possible to determine all activities necessary for slot execution. In this case by using a rule based on the roughness value can be chosen the needed activities and the machines tools for machining:

IF *R ≤ 0.8 µm* **THEN** *turning (roughing and finishing) + grinding*
IF *0,8 < R ≤ 3,2* **THEN** *turning (roughing and finishing)*
IF R > 3,2 *µm* **THEN** *turning (roughing)*

Hence, the necessary phases for slot realization are: the execution of the initial relief and the external cylindrical turning. Taking into account only the second phase, the formulas used in order to calculate the machining time are as follows:

Roughing passes $$NPs = \frac{P}{Pp} \quad (1)$$

Medium diameter $$Dm = \frac{Di + Df}{2} \quad (2)$$

Rotational speed $$n = \frac{1000 \cdot Vc}{\pi \cdot Dm} \quad (3)$$

Roughing feeding rate $$VAs = n \cdot As \quad (4)$$

Finishing feeding rate $$VAf = n \cdot Af \quad (5)$$

Working time

$$Time = \left(\frac{L + E}{VAs} \cdot NPs \right) \cdot 1.25 + \left(\frac{L + P + E}{VAf} \cdot NPf \right) \cdot 1.25 \quad (6)$$

Where Pp is the cutting depth, Vc the cutting speed, As the roughing feed, Af the finishing feed, NPf the pass number for finishing, E the extra traverse and 1,25 is used to consider the rapid traverse.

By linking a specific database where companies store the unit cost of each machine it is possible to quantify the feature cost. In order to completely estimate the cost of component it is also indispensable to define the cost framework. It is determined summing the cost of the stock with the machining cost, composed by fixed (cost which must be subdivided for the number of lot components, such as equipment cost) and variable cost (it is the direct cost of machining). In the same way is performed the welded assembly cost estimation; in this case before each component is separately evaluated and then the welding cost for assembling them.

4 LeanCost software system

The described approach has been implemented in a software tool called “LeanCost”. In figure 3 is represented the system structure.

This tool is a Windows-based application that currently can estimate the cost of components and welded assemblies. In particular it has been implemented taking into account the context of companies where Product Lifecycle Management (PLM) systems are present. PLM system contains engineering data such as CAD models, drawings and documents stored in the PLM database. LeanCost interacts with the PLM system in order to extract the needed geometric and non-geometric information.

The structure includes also specific databases about machine tools, materials and cutting parameters (cutting speed, setup time, etc.).

The LeanCost application supports three different user access levels:

- **Designer user:** the access is integrated within the CAD system user interface; the system performs automatically the cost analysis. As output he/she examines a cost report that highlights the different cost drivers. In this way the system suggests which factors should be changed.

- **Technologist user**: he/she inherits the cost analysis from the design phase; this user verifies the results and analyses various reports in order to plan the manufacturing activities. The technologist user can set the process and working cycle parameters.
- **Purchase department user**: this access level is limited to the cost reports; they are used to choose the most suitable suppliers.

As shown in figure 3 the LeanCost tool is composed of four main modules:

- **CAD Interface Module**: this module, that is developed using Visual Basic.NET programming language, analyses the CAD model and the related not geometrical information in order to identify the advanced manufacturing features. This module is linked to the PLM system (in this research is used Solid Edge.20, by Siemens Gmbh). The extraction of information from the CAD model is made by reliable classes and functions properly developed. They perform a topological analysis of all geometrical entities. The module generates as output an ordered set of advanced manufacturing features represented through geometrical entities (faces, loops, edges), dimensions, finishing, tolerances and physical properties (mass and density). This module identifies also the simple modelling features.
- **Process Allocation Module**: the set of ordered advanced manufacturing features and simple modelling features are converted in a set of operations using this module. Then all geometrical and physical data are elaborated in order to semi-automatically determine each manufacturing process. This tool establishes the necessary processes to manufacture the component, and it proposes possible machines tools with their cutting parameters. This module interacts with external databases that store machine tools, materials and cutting parameters.
- **Calculation Engine**: a stand-alone module automatically calculates the manufacturing time by using proper computation functions related to the different processes. Then it translates the manufacturing time in product cost.
- **Report Generation Module**: it manages all calculated data and processed by the other tools.

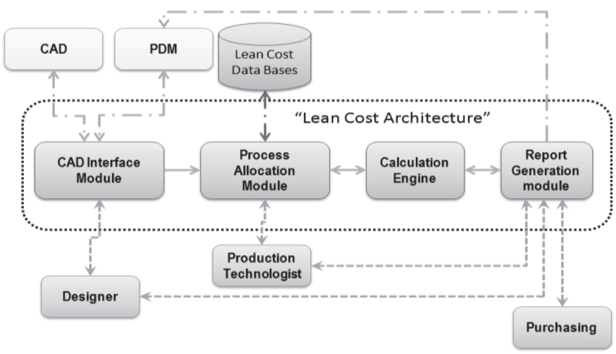

Fig. 3 LeanCost system structure

The different user interfaces are reported in figure 4.

A typical cost estimation work session implies the following stages. The designer works on the project for each product model (component or assembly). He/she uses the CAD system and generates the product cost estimation by using LeanCost. By analyzing the cost of different solutions, the designer can identify the best one. The created project is stored into a shared database, so the technologist can retrieve it. This user works on project elaborated by the designer in order to refine the estimated cost and modify, if necessary, the cost of specific processes. The calculated cost with notes related to the feasibility or improvements can be sent back to the designer. LeanCost is able to trace the communication between the design and process engineering departments. When this iterative process is completed the project is released. The released project by the manufacturing technologist, then, is ready to be sent to the purchasing department, for the supplier selection.

5 Experimentation and results discussion

LeanCost is a multi-users software system, because different user profiles can access to an estimation file, by using specific interfaces.

Fig. 4 Graphical User Interfaces (GUI) proposed to the "LeanCost"

The technologist interface used by technicians, allows them to manually define the production process by defining operations, adjusting each operation parameter and finally determining cost. In this way, this cost is recognized as "*standard cost*" that is cost used by purchaser to negotiate with company's suppliers. On the other hand, the LeanCost designer interface is used to estimate production cost during the embodiment design phase. LeanCost designer interface is like a "wizard", where step-by-step software automatically recognizes the manufacturing process and it calculates cost items for analyzed part or assembly. In this procedure, designer is an "*onlooker*" who confides in the final result proposed by software. For each estimated component through LeanCost designer interface, the designer has not introduced any manual information, then we can say that the final cost has been automatically calculated by LeanCost, starting from 3D CAD model. In order to evaluate accuracy of estimated cost numerous cases have been tested, within the fields of chip forming operations and carpentry.

Test cases have been chosen in collaboration with Biesse Group S.p.A., a world leader company producing woodworking machines. First of all has been defined a schema in order to gather data during testing phase. Information contained in this document, should be considered as to have a double function: to formalize the deviation between estimated and standard cost, both calculated using the two different LeanCost interfaces (one for designers and the other for production technologists) and to guide LeanCost improvement road map, in terms of algorithms and data within database.

The testing summary document (table 2) is constituted by several sections, each of them containing specific information, which will be used to draw appropriated conclusions. The first section is used to note the four cost items managed by LeanCost: working (milling, turning, bending, painting, heat treatments, etc.), stock (sheet metal, stock, forged components, etc.), accessory (tool change, part change, spindle change) and machines set-up (tools set-up, tools pre-setting, working test cycle, etc.). For each item, the percentage deviation has been calculated, in order to understand the main sources of error. This data, however, are not sufficient to give further information about the issues sources, because, the cost, for a common mechanical component, depends by thousands geometrical and technological parameters.

Three other groups of information have been further defined. The first one is used to store general information for tested component, such as the lot dimension (in case of small lots, the incidence of set-up cost on every component could be very high), recognized operations and number of operations whose have same geometrical parameters (dimensions) between standard and estimated cost.

The second group of information is used to characterize the stock. Regardless the stock type, its cost is calculated by its unitary cost (generally a cost for a unit weight) and weight (part weight plus scraps). Another information will be provided in order to see if LeanCost has been able to automatically detect the best and suitable stock to use for final product. This section will be used to explain deviation about stock cost.

The last part of this document contains the list of machines used to work the part or assembly. Operations are then grouped for their own machine (lathe, grinder, milling, laser cutting, bender, etc.). For each machine group, the following parameters will be defined: machine type (milling, grinder, etc), number of operations (operations performed by selected machine), working time (sum of working times for each operation done on this machine; the accessory times must not be taken into account), machine unitary cost, number of tools, time for tool and part change, and finally a Boolean value to indicate if the machine we are comparing for standard cost is equal to that one for estimated cost. This block of information are useful to determine what are the deviation sources for working, accessory and set-up costs.

LeanCost (designer interface) provides five wizards (automated procedures), which could be used to automatically estimate manufacturing cost for prismatic and axisymmetric components, beams, sheet metals and assemblies (the last ones are generally carpentry assemblies). Test components (as shown in figure 5) have been selected in order to validate these five procedures. They range in complexity for shape and manufacturing process from a minimum of 7 operations to a maximum of 193. As direct consequence, the total costs range from about 10€ to almost 130€. Stocks are included in a range of small grams (about 200 grams for small prismatic components, machined by millings) up to tens kilograms (about 40 kilograms in case of big sheet metals). The production dimension, instead, is ranging from very small lots (2 pieces) to small-medium ones (20 components). Tested components generally require turning, milling, boring, grinding, laser, oxyacetylene and beams cutting and bending, operations.

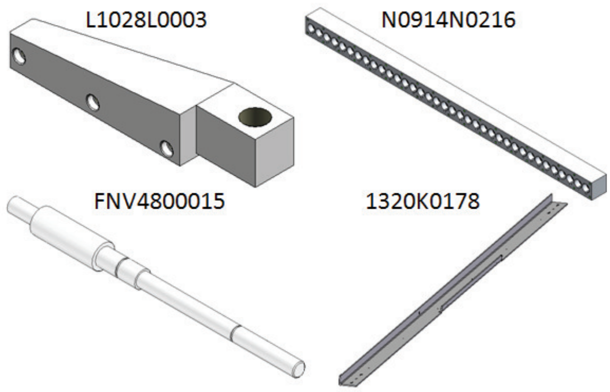

Fig. 5 components used for LeanCost testing

From the table 2 can be noted that achieved deviation is acceptable for axisymmetric, sheet metal and beams components, while it needs improvements in case of prismatic components.

By analyzing results gathered during testing period, further interesting considerations are listed. Some of them refer to misalignment between parameters (also a unitary cost is a parameter) within database and real parameters (for example the current cost of a commercial material), which cannot be considered as real bugs. Some parameters within database could be obsolete, because new technologies appeared on the market, such as new tools or machines, or the cost of raw material is changed due to the market dynamicity, and so on. A continuous maintenance work on databases will avoid this kind of issues.

The other group of issues refer, instead, to bugs or improvements required for LeanCost:

- algorithms to recognize operations from a 3D CAD model. The working cost depends by the operations recognized using manufacturing features recognition algorithms. Sometimes, a CAD model (in particular prismatic models machined with milling operations) are characterized by a very complex shape, where it is pretty difficult to identify the exact working schedule. Errors committed by software, for this group, are represented by the non-correct number of recognized operations and the non-exact geometry for the identified operation. When an estimate coming from the design phase with this errors, is opened by a production technicians, these errors are quite laborious to solve, because the working schedule should be manually double checked.

	Unit of measure	FNV4800015_axisymmetric Standard Cost	FNV4800015_axisymmetric Estimated Cost	N0914N0216_prismatic Standard Cost	N0914N0216_prismatic Estimated Cost	1320K0178_SheetMetal Standard Cost	1320K0178_SheetMetal Estimated Cost	1320K0160_Beam Standard Cost	1320K0160_Beam Estimated Cost	L1028L0003_Prsimatic Standard Cost	L1028L0003_Prsimatic Estimated Cost
Working cost	€	€ 3,44	€ 3,16	€ 72,48	€ 55,26	€ 14,47	€ 14,47	€ 1,08	€ 1,08	€ 4,05	€ 1,39
Stock cost	€	€ 0,22	€ 0,18	€ 20,25	€ 22,95	€ 29,25	€ 29,25	€ 8,65	€ 8,65	€ 16,53	€ 16,08
Accessory cost	€	€ 0,40	€ 0,56	€ 3,53	€ 4,07	€ 0,83	€ 0,83	€ 0,39	€ 3,07	€ 2,55	€ 3,77
Machine set-up cost	€	€ 24,58	€ 32,17	€ 33,85	€ 21,60	€ -	-	€ 1,81	€ 1,81	€ 4,71	€ 3,56
Total cost	€	**€ 28,64**	**€ 36,07**	**€ 130,11**	**€ 103,88**	**€ 44,55**	**€ 44,55**	**€ 11,93**	**€ 14,61**	**€ 27,84**	**€ 24,80**
Lot dimension		2	2	4	4	20	20	20	20	20	20
N° recognized operations		9	10	193	195	22	22	7	8	21	11
N° of operations with same geometric dimensions		-	8	-	191	-	22	-	7	-	5
Same stock		-	no	-	yes	-	yes	-	yes	-	yes
Unitary cost of stock material	€/Kg	0,98	0,73	3	3,4	0,7	0,7	0,9	0,9	9,5	9,5
Stock weight	Kg	0,22	0,25	6,75	6,75	41,78	41,78	9,6	9,6	1,74	1,67
N° machines		1	1	2	2	2	2	2	2	2	2
Machine 1											
Is equal		-	yes	-	yes	-	yes	-	yes	-	yes
Type		beam cutting	beam cutting	beam cutting	beam cutting	Laser cutting	Laser cutting	Beam cutting	Beam cutting	Beam cutting	Beam cutting
N° of operations		1	1	1	1	20	20	1	1	1	1
Working time	minute	0,11	0,24	0,85	0,85	5,22	5,22	0,14	0,14	0,41	0,41
Working time deviation	%	**118%**		**0%**		**0%**		**0%**		**0%**	
Unitary cost	€/h	25	25	25	25	90	90	25	25	25	25
Unitary cost machine tool deviation	%	**0%**		**0%**		**0%**		**0%**		**0%**	
N° of tools		-	-	-	-	-	-	-	-	-	-
Time for tool change	minute	-	-	-	-	-	-	-	-	-	-
Time for piece change	minute	-	-	-	-	-	-	-	-	-	-
Machine 2											
Is equal		-	no	-	no	-	yes	-	yes	-	no
Type		Lathe	Lathe	Milling	Milling	Bender	Bender	Milling	Milling	Milling	Milling
N° of operations		8	9	192	194	2	2	6	7		
Working time	minute	4,48	4,83	96,16	94,13	4	4	1,75	1,75	5,17	2,09
Working time deviation	%	**8%**		**-2%**		**0%**		**0%**		**-60%**	
Unitary cost	€/h	45	38	45	35	99,5	99,5	35	35	45	35
Unitary cost machine tool deviation	%	**-16%**		**-22%**		**0%**		**0%**		**-22%**	
N° of tools		6	10	17	19	-	-	2	2	15	14
Time for tool change	minute	0,08	0,08	0,2	0,1	-	-	0,2	0,1	0,1	0,1
Time for piece change	minute	0,05	0,05	0,3	5	-	-	0,3	5	1	5
		Deviation	**Reason**	**Deviation**	**Reason**	**Deviation**	**Reason**	**Deviation**	**Reason**	**Deviation**	**Reason**
Working cost deviation	%	**-8%**		**-24%**		**0%**		**0%**		**-66%**	
Stock Cost deviation	%	**-18%**		**13%**		**0%**		**0%**		**-3%**	
Accessory cost deviation	%	**40%**		**15%**		**0%**		**687%**		**48%**	
Machine set-up cost deviation	%	**31%**		**-36%**		**0%**		**0%**		**-24%**	
Total cost deviation	%	**26%**		**-20%**		**0%**		**22%**		**-11%**	

Tab. 2 Results concerning tested components.

- algorithms to choose machines. The machine choice is very important because it influences three cost items: working, accessory and set-up. Working time depends by the machine because each machine has its own cutting speed, feeding speed, etc. and unitary cost, accessory cost because each machine has specific times for tool change or part change and, finally, the set up cost because each machine has characteristic set up procedures. The incidence on the final component cost, given by the machine choice, it increases while the lot dimension decreases, because set-up cost becomes more important. The machine has to be chosen according to the shape of the component to be machined, its weight, the production lot dimension, needs of specific machining operations, etc.

- to introduce new algorithms, formulas or rules to calculate specific parameters. Some parameters have been supposed constant, such as the time to change a part on a machine (accessory time). This is not sufficiently correct because changing the components dimensions and weight, this time can noticeably change.

- algorithms to calculate tools. The tools number influences both accessory (each time a tool is used it should be changed) and set-up cost (each tool must be loaded on machine and then set). The algorithms used to calculate the tools requires an improvement, because the tools number, in several cases, is different respect real situation.

Taking a look to the results analyzed during testing period, the following conclusions could be derived:

- algorithms used to calculate the stock cost are generally reliable. Sometimes the standard cost is equal to estimated one, and, in case of great deviations (> 10%), the issue is given by the misalignment of unitary stock cost within database with real values. The kind of stock chosen by LeanCost is often exact;

- the manufacturing features recognition algorithms used to estimate sheet metals and beams are very reliable, sometimes standard cost and estimated one are the same. In case of prismatic (milling operations) or axisymmetric components, further improvements are required in order to maintain the working cost deviation less than 10%;

- new algorithms to chose machine should be developed. Now, there is a default machine for each category (milling, lathe), but this solution is too simple to consider real needs;

Conclusions and future developments

This paper describes a knowledge system that can be used in three different company departments (design, manufacturing plan and purchasing) in order to develop a shared cost model based on analytical methodologies for cost estimation of components and welded assemblies. When the user is the designer, LeanCost is able to automatically estimate the production costs of many kinds of components, prismatic, machined with milling, axisymmetric, cogwheel, sheet metals, beams and assemblies. Common operations managed by this software are: milling, turning, grinding, toothing, broaching, laser and oxyacetylene cutting, bending, beam cutting, welding, heat treatments, superficial covering, and forming (foundry, forming, etc.).

The developed system has been tested on several and different components, in order to analyze its reliability. For some components, results are very good, because the estimated cost is almost equal to real and standard cost; deviation is about 10%. For some other type of components and operations, certain improvements are required in order to maintain the reliability under an error threshold. These improvements mainly concerns algorithms for feature recognition and for the best machine choosing. Algorithms for stock calculation can be considered reliable, because they often have returned valid values. The objective is to maintain, for every component, the deviation between estimated cost and standard cost less than 10%. Designer should be able to know the cost of a component, in a completely automatic way, without giving no detailed information, with a reliability of 10%. A single component should be estimated in few minutes, from a minimum of two, for easy components, to 5 minutes, for complicated ones.

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